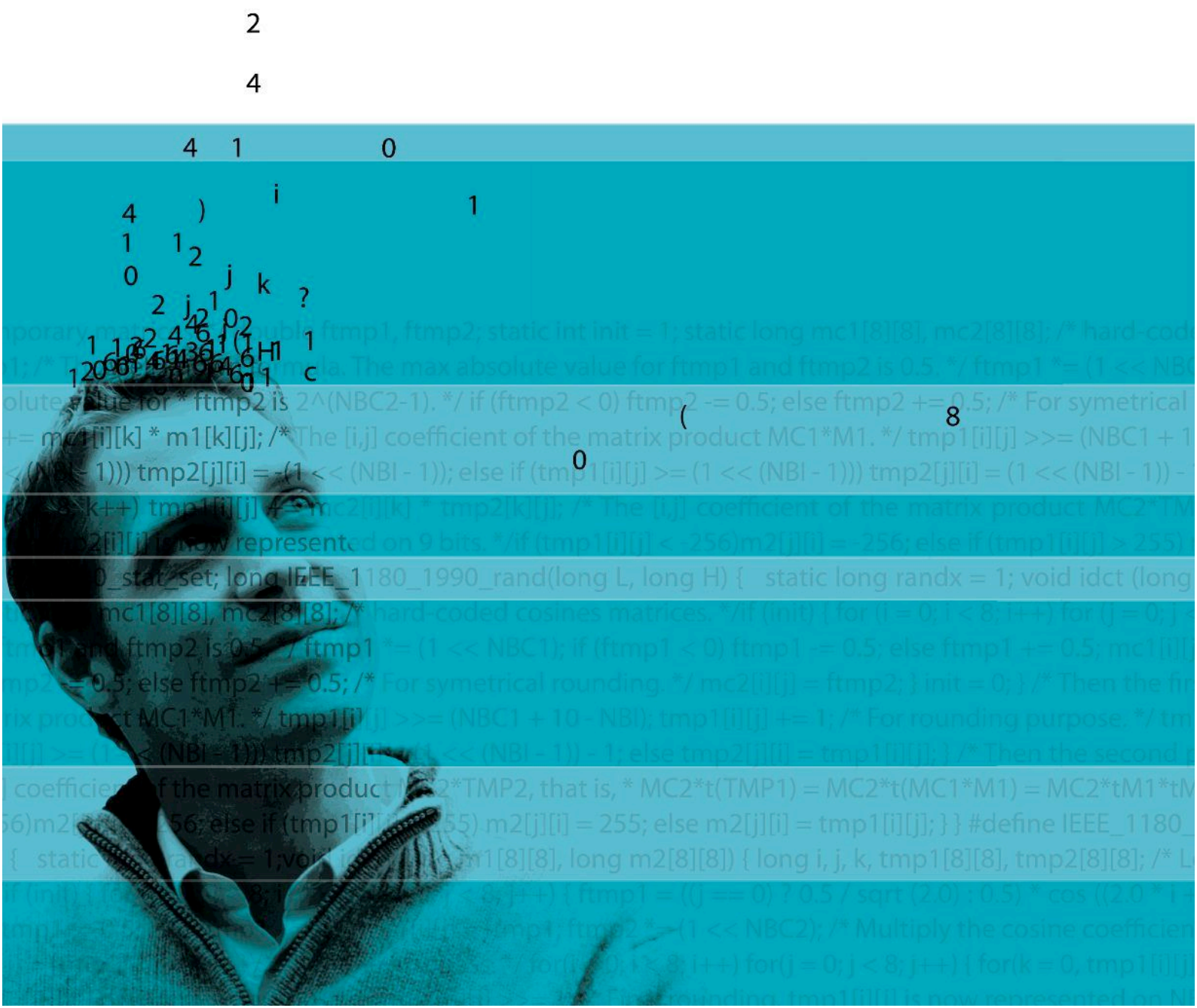
frama C

Software Analyzers

RTE — Runtime Error Annotation Generation



Frama-C's RTE plug-in

for Frama-C 19.0-beta2 (Potassium)

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Contents

Chapter 1

Introduction

1.1 RTE plug-in

This document is a reference manual for the annotation generator plug-in called RTE. The aim of the RTE plug-in is to automatically generate annotations for:

- common runtime errors, such as division by zero, signed integer overflow or invalid memory access;
- unsigned integer overflows, which are allowed by the C language but may pose problem to solvers;

In a modular proof setting, the main purpose of the RTE plug-in is to seed more advanced plug-ins (such as the weakest-preconditions generation plug-in [2]) with proof obligations. Annotations can also be generated for their own sake in order to guard against runtime errors. The reader should be aware that discharging such annotations is much more difficult than simply generating them, and that there is no guarantee that a plug-in such as Frama-C's value analysis [3] will be able to do so automatically in all cases.

RTE performs syntactic constant folding in order not to generate trivially valid annotations. Constant folding is also used to directly flag some annotations with an invalid status. RTE does not perform any kind of advanced value analysis, and does not stop annotation generation when flagging an annotation as invalid, although it may generate fewer annotations in this case for a given statement.

Like most Frama-C plug-ins, RTE makes use of the hypothesis that signed integers have a two's complement representation, which is a common implementation choice. Also note that annotations are dependent of the *machine dependency* used on Frama-C command-line, especially the size of integer types.

The C language ISO standard [4] will be referred to as ISO C99 (of which specific paragraphs are cited, such as 6.2.5.9).

1.2 Runtime errors

A runtime error is a usually fatal problem encountered when a program is executed. Typical fatal problems are segmentation faults (the program tries to access memory that it is not

allowed to access) and floating point exceptions (for instance when dividing an integer by zero: despite its name, this exception does not only occur when dealing with floating point arithmetic). A C program may contain "dangerous" constructs which under certain conditions lead to runtime errors when executed. For instance evaluation of the expression `u / v` will always produce a floating point exception when `v = 0` holds. Writing to an out-of-bound index of an array may result in a segmentation fault, and it is dangerous even if it fails to do so (other variables may be overwritten). The goal of this Frama-C plug-in is to detect a number of such constructs, and to insert a corresponding logical annotation (a first-order property over the variables of the construct) ensuring that, whenever this annotation is satisfied before execution of the statement containing the construct, the potential runtime error associated with the expression will not happen. Annotation checking can be performed (at least partially) by Frama-C value analysis plug-in [3], while more complicated properties may involve other plug-ins and more user interaction.

At this point it is necessary to define what one means by a "dangerous" construct. ISO C99 lists a number of *undefined* behaviors (the program construct can, at least in certain cases, be erroneous), a number of *unspecified* behaviors (the program construct can be interpreted in at least two ways), and a list of *implementation-defined* behaviors (different compilers and architectures implement different behaviors). Constructs leading to such behaviors are considered dangerous, even if they do not systematically lead to runtime errors. In fact an undefined behavior must be considered as potentially leading to a runtime error, while unspecified and implementation-defined behaviors will most likely result in portability problems. error prevention.

An example of an undefined behavior (for the C language) is *signed integer overflow*, which occurs when the (exact) result of a signed integer arithmetic expression can not be represented in the domain of the type of the expressions. For instance, supposing that an `int` is 32-bits wide, and thus has domain `[-2147483648,2147483647]`, and that `x` is an `int`, the expression `x+1` performs a signed integer overflow, and therefore has an undefined behavior, if and only if `x` equals `2147483647`. This is independent of the fact that for most (if not all) C compilers and 32-bits architectures, one will get `x+1 = -2147483648` and no runtime error will happen. But by strictly conforming to the C standard, one cannot assert that the C compiler will not in fact generate code provoking a runtime error in this case, since it is allowed to do so. Also note that from a security analysis point of view, an undefined behavior leading to a runtime error classifies as a denial of service (since the program terminates), while a signed integer overflow may very well lead to buffer overflows and execution of arbitrary code by an attacker. Thus not getting a runtime error on an undefined behavior is not necessarily a desirable behavior.

On the other hand, note that a number of behaviors classified as implementation-defined by the ISO standard are quite painful to deal with in full generality. In particular, ISO C99 allows either *sign and magnitude*, *two's complement* or *one's complement* for representing signed integer values. Since most if not all "modern" architectures are based on a *two's complement* representation (and that compilers tend to use the hardware at their disposal), it would be a waste of time not to build verification tools by making such wide-ranging and easily checkable assumptions. **Therefore RTE uses the hypothesis that signed integers have a *two's complement* representation.**

1.3 Other annotations generated

RTE may also generate annotations that are not related to runtime errors:

- absence of unsigned overflows checking. Although unsigned overflows are well-defined, some plug-ins may wish to avoid them.
- accesses to arrays that are embedded in a struct occur withing valid bounds. This is stricter than verifying that the accesses occurs within the struct.

Chapter 2

Runtime error annotation generation

2.1 Integer operations

According to 6.2.5.9, operations on unsigned integers "can never overflow" (as long as the result is defined, which excludes division by zero): they are reduced modulo a value which is one greater than the largest value of their unsigned integer type (typically 2^n for n-bit integers). So in fact, arithmetic operations on unsigned integers should really be understood as modular arithmetic operations (the modulus being the largest value plus one).

On the other hand, an operation on *signed* integers might overflow and this would produce an undefined behavior. Hence, a signed integer operation is only defined if its result (as a mathematical integer) falls into the interval of values corresponding to its type (e.g. `[INT_MIN,INT_MAX]` for `int` type, where the bounds `INT_MIN` and `INT_MAX` are defined in the standard header `limits.h`). Therefore, signed arithmetic is true integer arithmetic as long as intermediate results are within certain bounds, and becomes undefined as soon as a computation falls outside the scope of representable values of its type.

The full list of arithmetic and logic operations which might overflow is presented hereafter. Most of these overflows produce undefined behaviors, but some of them are implementation defined and indicated as such.

2.1.1 Addition, subtraction, multiplication

These arithmetic operations may not overflow when performed on signed operands, in the sense that the result must fall in an interval which is given by the type of the corresponding expression and the macro-values defined in the standard header `limits.h`. A definition of this file can be found in the `share` directory of Frama-C.

type	representable interval
signed char	[SCHAR_MIN, SCHAR_MAX]
signed short	[SHRT_MIN,SHRT_MAX]
signed int	[INT_MIN,INT_MAX]
signed long int	[LONG_MIN,LONG_MAX]
signed long long int	[LLONG_MIN,LLONG_MAX]

Since RTE makes the assumption that signed integers are represented in 2's complement, the interval of representable values also corresponds to $[-2^{n-1}, 2^{n-1} - 1]$ where n is the number

of bits used for the type (sign bit included, but not the padding bits if there are any). The size in bits of a type is obtained through `Cil.bitsSizeOf: typ -> int`, which bases itself on the machine dependency option of Frama-C. For instance by using `-machdep x86_32`, we have the following:

type	size in bits	representable interval
signed char	8	[-128,127]
signed short	16	[-32768,32767]
signed int	32	[-2147483648,2147483647]
signed long int	32	[-2147483648,2147483647]
signed long long int	64	[-9223372036854775808,9223372036854775807]

Frama-C annotations added by plug-ins such as RTE may not contain macros since preprocessing is supposed to take place beforehand (user annotations at the source level can be taken into account by using the `-pp-annot` option). As a consequence, annotations are displayed with big constants such as those appearing in this table.

Example 2.1 *Here is a RTE-like output in a program involving* signed long int *with an* `x86_32` *machine dependency:*

```
int main(void) {
  signed long int lx, ly, lz;

  /*@ assert rte: signed_overflow: -2147483648 <= lx*ly; */
  /*@ assert rte: signed_overflow: lx*ly <= 2147483647; */
  lz = lx * ly;

  return 0;
}
```

The same program, but now annotated with an `x86_64` *machine dependency (option* `-machdep x86_64`*):*

```
int main(void) {
  signed long int lx, ly, lz;

  /*@ assert rte: signed_overflow: -9223372036854775808 <= lx*ly; */
  /*@ assert rte: signed_overflow: lx*ly <= 9223372036854775807; */
  lz = lx * ly;

  return 1;
}
```

The difference comes from the fact that signed long int *is 32-bit wide for* `x86_32`*, and 64-bit wide for* `x86_64`*.*

2.1.2 Signed downcasting

Note that arithmetic operations usually involve arithmetic conversions. For instance, integer expressions with rank lower than int are promoted, thus the following program:

```
int main(void) {
  signed char cx, cy, cz;
```

```
  cz = cx + cy;
  return 0;
}
```

is in fact equivalent to:

```
int main(void) {
  signed char cx, cy, cz;

  cz = (signed char)((int)cx + (int)cy);
  return 0;
}
```

Since a signed overflow can occur on expression `(int)cx + (int)cy`, the following annotations are generated by the RTE plug-in:

```
/*@ assert rte: signed_overflow: -2147483648 <= (int)cx+(int)cy; */
/*@ assert rte: signed_overflow: (int)cx+(int)cy <= 2147483647; */
```

This is much less constraining than what one would want to infer, namely:

```
/*@ assert (int)cx+(int)cy <= 127; */
/*@ assert -128 <= (int)cx+(int)cy; */
```

Actually, by setting the option `-warn-signed-downcast` (which is unset by default), the RTE plug-in infers these second (stronger) assertions when treating the cast of the expression to a `signed char`. Since the value represented by the expression cannot in general be represented as a `signed char`, and following ISO C99 paragraph 6.3.1.3.3 (on downcasting to a signed type), an *implementation-defined behavior* happens whenever the result falls outside the range `[-128,127]`. Thus, with a single annotation, the RTE plug-in prevents both an undefined behavior (signed overflow) and an implementation defined behavior (signed downcasting). Note that the annotation for signed downcasting always entails the annotation for signed overflow.

2.1.3 Unary minus

The only case when a (signed) unary minus integer expression `-expr` overflows is when `expr` is equal to the minimum value of the integer type. Thus the generated assertion is as follows:

```
int ix;
// some code
/*@ assert rte: signed_overflow: -2147483647 <= ix; */
ix = - ix;
```

2.1.4 Division and modulo

As of ISO C99 paragraph 6.5.5, an undefined behavior occurs whenever the value of the second operand of operators `/` and `%` is zero. The corresponding runtime error is usually referred to as "division by zero". This may happen for both signed and unsigned operations.

```
unsigned int ux;
// some code
/*@ assert rte: division_by_zero: ux != 0; */
ux = 1 / ux;
```

In 2's complement representation and for signed division, dividing the minimum value of an integer type by -1 overflows , since it would give the maximum value plus one. There is no such rule for signed modulo, since the result would be zero, which does not overflow.

```
int x,y,z;
// some code
/*@ assert rte: division_by_zero: x != 0; */
/*@ assert rte: signed_overflow: y/x <= 2147483647; */
z = y / x;
```

2.1.5 Bitwise shift operators

ISO C99 paragraph 6.5.7 defines undefined and implementation defined behaviors for bitwise shift operators. The type of the result is the type of the promoted left operand.

The undefined behaviors are the following:

- the value of the right operand is negative or is greater than or equal to the width of the promoted left operand:

```
int x,y,z;

/*@ assert rte: shift: 0 <= y < 32; */
z = x << y; // same annotation for z = x >> y;
```

- in `E1 << E2`, `E1` has signed type and negative value:

```
int x,y,z;

/*@ assert rte: shift: 0 <= x; */
z = x << y;
```

- in `E1 << E2`, `E1` has signed type and nonnegative value, but the value of the result $\mathrm{E1} \times 2^{\mathrm{E2}}$ is not representable in the result type:

```
int x,y,z;

/*@ assert rte: signed_overflow: x<<y <= 2147483647; */
z = x << y;
```

There is also an implementation defined behavior if in `E1 >> E2`, `E1` has signed type and negative value. This case corresponds to the arithmetic right-shift, usually defined as signed division by a power of two, with two possible implementations: either by rounding the result towards minus infinity (which is standard) or by rounding towards zero. RTE generates an annotation for this implementation defined behavior.

```
int x,y,z;

/*@ assert rte: shift: 0 <= x; */
z = x << y;
```

Example 2.2 *The following example summarizes RTE generated annotations for bitwise shift operations, with* `-machdep x86_64`*:*

```
long x,y,z;

/*@ assert rte: shift: 0 <= y < 64; */
/*@ assert rte: shift: 0 <= x; */
/*@ assert rte: signed_overflow: x<<y <= 9223372036854775807; */
z = x << y;

/*@ assert rte: shift: 0 <= y < 64; */
/*@ assert rte: shift: 0 <= x; */
z = x >> y;
```

2.2 Left-values access

Dereferencing a pointer is an undefined behavior if:

- the pointer has an invalid value: null pointer, misaligned address for the type of object pointed to, address of an object after the end of its lifetime (see ISO C99 paragraph 6.5.3.2.4);
- the pointer points one past the last element of an array object: such a pointer has a valid value, but should not be dereferenced (ISO C99 paragraph 6.5.6.8).

The RTE plug-in generates annotations to prevent this type of undefined behavior in a systematic way. It does so by deferring the check to the ACSL built-in predicate `valid(p)`: `valid(s)` (where `s` is a set of terms) holds if and only if dereferencing any p ∈ s is safe (i.e. points to a safely allocated memory location). A distinction is made for read accesses, that generate `\valid_read(p)` assertions (the locations must be at least readable), and write accesses, for which `\valid(p)` annotations are emitted (the locations must be readable and writable).

Since an array subscripting `E1[E2]` is identical to `(*((E1) + (E2)))` (ISO C99 paragraph 6.5.2.1.2), the "invalid access" undefined behaviors naturally extend to array indexing, and RTE will generate similar annotations. However, when the array is known, RTE attempts to generate simpler assertions. Typically, on an access `t[i]` where `t` has size `10`, RTE will generate two assertions `0 <= i` and `i < 10`, instead of `\valid(&t[i])`.

The kernel option `-safe-arrays` (or `-unsafe-arrays`) influences the annotations that are generated for an access to a multi-dimensional array, or to an array embedded in a struct. Option `-safe-arrays`, which is set by default in Frama-C, requires that all syntactic accesses to such an array remain in bound. Thus, if the field `t` of the struct `s` has size `10`, the access `s.t[i]` will generate an annotation `i < 10`, even if some fields exist after `t` in `s`.[1] Similarly, if `t` is declared as `int t[10][10]`, the access `t[i][j]` will generate assertions `0 <= i < 10` and `0 <= j < 10`, even though `t[0][12]` is also `t[1][2]`.

Finally, dereferencing a pointer to a functions leads to the emission of a `\valid_function` predicate, to protect against a possibly invalid pointer (ISO C99 6.3.2.3:8). Those assertions are generated provided option `-rte-pointer-call` is set.

Example 2.3 *An example of RTE annotation generation for checking the validity of each memory access:*

[1] Thus, by default, RTE is more stringent than the norm. Use option `-unsafe-arrays` if you want to allow code such as `s.t[12]` in the example above.

```
extern void f(int* p);
int i;
unsigned int j;

int main(void) {
  int *p;
  int tab[10];

  /*@ assert rte: mem_access: \valid(p); */
  *p = 3;

  /*@ assert rte: index_bound: 0 <= i; */
  /*@ assert rte: index_bound: i < 10; */
  /*@ assert rte: mem_access: \valid_read(p); */
  tab[i] = *p;

  /*@ assert rte: mem_access: \valid(p+1); */
  /*@ assert rte: index_bound: j < 10; */
  // No annotation 0 <= j, as j is unsigned
  *(p + 1) = tab[j];

  return 0;
}
```

Example 2.4 *An example of memory access validity annotation generation for structured types, with options* `-safe-arrays` *and* `-rte-pointer-call` *set.*

```
struct S {
   int val;
   struct S *next;
};

struct C {
   struct S cell[5];
   int (*f)(int);
};

struct ArrayStruct {
   struct C data[10];
};

unsigned int i, j;

int main() {
  int a;
  struct ArrayStruct buff;
  // some code

  /*@ assert rte: index_bound: i < 10; */
  /*@ assert rte: index_bound: j < 5; */
  /*@ assert rte: mem_access: \valid_read(&(buff.data[i].cell[j].next)->val); */
  a = (buff.data[i].cell[j].next)->val;

  /*@ assert rte: index_bound: i < 10; */
  /*@ assert rte: function_pointer: \valid_function(buff.data[i].f); */
  (*(buff.data[i].f))(a);
```

```
  return 0;
}
```

Notice the annotation generated for the call `(*(buff.data[i].f))(a)`.

2.3 Unsigned overflow annotations

ISO C99 states that *unsigned* integer arithmetic is modular: overflows do not occur (paragraph 6.2.5.9 of ISO C99). On the other hand, most first-order solvers used in deductive verification (excluding dedicated bit-vector solvers such as [1]) either provide only non-modular arithmetic operators, or are much more efficient when no modulo operation is used besides classic full-precision arithmetic operators. Therefore RTE offers a way to generate assertions preventing unsigned arithmetic operations to overflow (*i.e.* involving computation of a modulo).

Operations which are considered by RTE regarding unsigned overflows are addition, subtraction, multiplication. Negation (unary minus), left shift. and right shift are not considered. The generated assertion requires the result of the operation (in non-modular arithmetic) to be less than the maximal representable value of its type, and nonnegative (for subtraction).

Example 2.5

The following file only contains unsigned arithmetic operations: no assertion is generated by RTE by default.

```
unsigned int f(unsigned int a, unsigned int b) {
  unsigned int x, y;
  x = a * (unsigned int)2;
  y = b - x;
  return y;
}
```

To generate assertions w.r.t. unsigned overflows, options `-warn-unsigned-overflow` *must be used. Here is the resulting file on a 32 bits target architecture (*`-machdep x86_32`*):*

```
unsigned int f(unsigned int a, unsigned int b) {
  unsigned int x, y;
  /*@ assert rte: unsigned_overflow: 0 <= a*(unsigned int)2; */
  /*@ assert rte: unsigned_overflow: a*(unsigned int)2 <= 4294967295; */
  x = a * (unsigned int)2;
  /*@ assert rte: unsigned_overflow: 0 <= b-x; */
  /*@ assert rte: unsigned_overflow: b-x <= 4294967295; */
  y = b - x;
  return y;
}
```

2.4 Unsigned downcast annotations

Downcasting an integer type to an unsigned type is a well-defined behavior, since the value is converted using a modulo operation just as for unsigned overflows (ISO C99 paragraph 6.3.1.3.2). The RTE plug-in offers the possibility to generate assertions preventing such occurrences of modular operations with the `-warn-unsigned-downcast` option.

Example 2.6

On the following example, the sum of two int *is returned as an unsigned char:*

```
unsigned char f(int a, int b) {
  return a+b;
}
```

Using RTE with the `-warn-unsigned-downcast` *option gives the following result:*

```
unsigned char f(int a, int b) {
  unsigned char __retres;
  /*@ assert rte: unsigned_downcast: a+b <= 255; */
  /*@ assert rte: unsigned_downcast: 0 <= a+b; */
  /*@ assert rte: signed_overflow: -2147483648 <= a+b; */
  /*@ assert rte: signed_overflow: a+b <= 2147483647; */
  __retres = (unsigned char)(a + b);
  return (__retres);
}
```

2.5 Cast from floating-point to integer types

Casting a value from a real floating type to an integer type is allowed only if the value fits within the integer range (ISO C99 paragraph 6.3.1.4), the conversion being done with a truncation towards zero semantics for the fractional part of the real floating value. The RTE plug-in generates annotations that ensure that no undefined behavior can occur on such casts.

```
int f(float v) {
  int i = (int)(v+3.0f);
  return i;
}
```

Using RTE with the `-rte-float-to-int` option, which is set by default, gives the following result:

```
int f(float v) {
  int i;
  /*@ assert rte: float_to_int: v+3.0f < 2147483648; */
  /*@ assert rte: float_to_int: -2147483649 < v+3.0f; */
  i = (int)(v + 3.0f);
  return i;
}
```

2.6 Expressions not considered by RTE

An expression which is the operand of a sizeof (or `__alignof`, a GCC operator parsed by Cil) is ignored by RTE, as are all its sub-expressions. This is an approximation, since the operand of sizeof may sometimes be evaluated at runtime, for instance on variable sized arrays: see the example in ISO C99 paragraph 6.5.3.4.7. Still, the transformation performed by Cil on the source code actually ends up with a statically evaluated sizeof (see the example below). Thus the approximation performed by RTE seems to be on the safe side.

Example 2.7 *Initial source code:*

```
#include <stddef.h>

size_t fsize3(int n) {
  char b[n + 3]; // variable length array
  return  sizeof  b; // execution time sizeof
}

int main() {
  return fsize3(5);
}
```

Output obtained with `frama-c -print` *with* `gcc` *preprocessing:*

```
typedef unsigned long size_t;
/* compiler builtin:
   void *__builtin_alloca(unsigned int); */
size_t fsize3(int n)
{
  size_t __retres;
  char *b;
  unsigned int __lengthofb;
  {
    /*undefined sequence*/
    __lengthofb = (unsigned int)(n + 3);
    b = (char *)__builtin_alloca(sizeof(*b) * __lengthofb);
  }
  __retres = (unsigned long)(sizeof(*b) * __lengthofb);
  return __retres;
}

int main(void)
{
  int __retres;
  size_t tmp;
  tmp = fsize3(5);
  __retres = (int)tmp;
  return __retres;
}
```

2.7 Undefined behaviors not covered by RTE

One should be aware that RTE only covers a small subset of all possible undefined behaviors (see annex J.2 of [4] for a complete list).

In particular, undefined behaviors related to the following operations are not considered:

- Use of relational operators for the comparison of pointers that do not point to the same aggregate or union (ISO C99 6.5.8)
- Demotion of a real floating type to a smaller floating type producing a value outside of the representable range (ISO C99 6.3.1.5)
- Conversion between two pointer types produces a result that is incorrectly aligned (ISO C99 6.3.2.3)

- Use of a variable with automatic storage duration before its initialization (ISO C99 6.7.8.10): such a variable has an indeterminate value

Chapter 3

Plug-in Options

Enabling RTE plug-in is done by adding `-rte` on the command-line of Frama-C. The plug-in then selects every C function which is in the set defined by the `-rte-select`: if no explicit set of functions is provided by the user, all C functions defined in the program are selected. Selecting the kind of annotations which will be generated is performed by using other RTE options (see fig. 3.1 and 3.2 for a summary).

Pretty-printing the output of RTE and relaunching the plug-in on the resulting file will generate duplicated annotations, since the plug-in does not check existing annotations before generation. This behaviour does not happen if RTE is used in the context of a Frama-C project [5]: the annotations are not generated twice.

Option	Type (Default)	Description
`-warn-unsigned-overflow`	boolean (false)	Generate annotations for unsigned overf (not entailed by `-rte-all`)
`-warn-unsigned-downcast`	boolean (false)	Generate annotations for unsigned int downcast (not entailed by `-rte-all`)
`-warn-signed-overflow`	boolean (true)	Generate annotations for signed overflows
`-warn-signed-downcast`	boolean (false)	Generate annotations for signed integer do cast
`-warn-left-shift-negative`	boolean (true)	Generate annotations for left shift on nega values
`-warn-right-shift-negative`	boolean (false)	Generate annotations for right shift on nega values
`-warn-invalid-bool`	boolean (true)	Generate annotations for `_Bool` trap represe tions
`-warn-special-float`	string: `non-finite`, (`nan`) or `none`	generate annotations when special floats are duced: infinite floats or NaN (by default), on NaN or never.

Table 3.1: Frama-C kernel options, impacting RTE

Option	Type (Default)	Description
`-rte`	boolean (false)	Enable RTE plug-in
`-rte-div`	boolean (false)	Generate annotations for division by zero
`-rte-shift`	boolean (false)	Generate annotations for left and right shift value out of bounds
`-rte-mem`	boolean (false)	Generate annotations for validity of left-values access
`-rte-float-to-int`	boolean (true)	Generate annotations for casts from floating-point to integer
`-rte-trivial-annotations`	boolean (true)	Generate all annotations even when they trivially hold
`-rte-warn`	boolean (true)	Emit warning on broken annotations
`-rte-select`	set of function (all)	Run plug-in on a subset of C functions

Table 3.2: RTE options

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